The Suitability of Objective Motion Criteria for Rotorcraft Manoeuvres

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A lack of guidance exists for the tuning of motion platforms for rotorcraft flight simulation. This is despite the widespread use of systems worldwide and the requirement for their use for the highest level of training simulators. In this paper, the state-of-the-art fixed-wing objective tuning methodology, the Objective Motion Cueing Test (OMCT), is applied to a typical rotorcraft manoeuvre. The goal of the investigation is to determine whether pilots observe negative transfer of training (ToT) when using different motion configurations. Results show large changes in subjective opinion following modifications to motion parameters. Pilot opinion was generally in disagreement with current fixed-wing 'fidelity boundaries'. The largest difference observed was the task performance time, which was found to increase with motion amplitude. Changes in objective performance parameters were smaller than subjective results. Results show the requirement for additional efforts to define suitable rotorcraft fidelity boundaries to eliminate negative ToT.

Nomenclature

H_i	=	Frequency-dependent amplitude response in the $i-$th axis $\{i = f_x, f_y, f_z, p, q, r\}$, $-$
H_{hp_i}	=	High-pass motion filter, $i-$th axis
$\angle H_i$	=	Frequency-dependent phase response in the $i-$th axis, deg
$H_{i/j}$	=	Amplitude response gain in $i-$th axis due to input in $j-$th axis, $-$
K_i	=	Motion gain in the $i-$th axis, $-$
L_{IS}	=	Transformation matrix from simulator to inertial coordinate system
R_{err}	=	Radius error during completion of pirouette manoeuvre, m
RMS_ϕ	=	Root-mean square of roll attitude, deg
RMS_θ	=	Root-mean square of pitch attitude, deg
S_I	=	Platform displacement, m
T_S	=	Transformation matrix to Euler angle accelerations
$f_{x_{AA}}, f_{y_{AA}}, f_{z_{AA}}$	=	Surge, sway, heave specific force at cockpit reference point (pilot seat), m/s^2
g, g_I	=	Acceleration due to gravity, m/s^2
p, q, r	=	Roll, pitch, yaw angular rate, deg/s
$\dot{p}_{AA}, \dot{q}_{AA}, \dot{r}_{AA}$	=	Roll, pitch, yaw acceleration, deg/s^2
ΔG_i	=	Change in motion response gain in the $i-$th axis, $-$
$\Delta \Phi_i$	=	Change in motion response phase in the $i-$th axis, deg
β_s	=	Simulator angular displacements, deg
ϕ, θ	=	Roll, pitch attitude of vehicle, rad, deg
ϕ_s	=	Roll attitude of simulator, rad
ϕ_{max}, θ_{max}	=	Maximum roll, pitch attitude, deg

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ACT/FHS	Active Control Technology / Flying Helicopter Simulator
ADS	Aeronautical Design Standard
AVES	Air Vehicle Simulator
BWR	Bedford Workload Rating
CWA	Classical Washout Algorithm
DEF-STD	Defence Standard
DLR	German Aerospace Center (Deutsches Zentrum für Luft- und Raumfahrt)
FAA	Federal Aviation Administration
FSTD	Flight Simulation Training Device
GS	Groundspeed
HP	High Pass
HQ(R)	Handling Qualities (Ratings)
LP	Low Pass
MTE	Mission Task Element
MR	Motion Rating
OMCT	Objective Motion Cueing Test
RMS	Root Mean Square
ToT	Transfer of Training
VMS	Vertical Motion Simulator

I. Introduction

A number of objective methods exist to determine the suitability of motion settings. However, the adoption of these techniques to training devices is limited and sporadic. This is despite calls from regulatory authorities to improve the techniques to determine the fidelity of motion systems, and enhance current subjective evaluation processes.[1] Furthermore, the proposed Objective Motion Cueing Test (OMCT)[2] technique contained within ICAO 9625[3] currently features only advisory 'boundaries', which have not been rigorously evaluated. From the academic field, a number of measures exist for tuning motion systems, including parameter settings[4–6] and advice to avoid spurious and false cues.[7,8] Again, these methods are not often employed in training simulators.

Further research must be conducted to show the benefit of employing these methods, particularly with respect to training efficacy. Techniques developed in the academic environment are often not readily applicable to challenges facing industry, particularly with respect to determining transfer of training (ToT) effectiveness. The OMCT is one technique that has been proposed and tested through collaboration with industry.[2] For fixed-wing aircraft, preliminary boundaries have been defined based upon the existing configurations used in a range of simulation devices. An example from these boundaries is shown for the roll axis in Fig. 1.

Although these practical boundaries have been developed, the resulting fidelity relies on the initial tuning undertaken, and training benefit has yet to be quantified. Now the academic environment must rigorously test OMCT to determine whether the previously proposed fidelity boundaries are appropriate. This has been initiated by a number of recent studies concerning fixed-wing flying tasks.[9–11] Preliminary efforts have also been undertaken for rotorcraft simulation devices.[2,12] This paper seeks to expand on this research, and present an initial evaluation of OMCT boundaries for a typical rotorcraft flight manoeuvre. A pirouette manoeuvre is completed using a number of motion configuration settings. These have been tuned to replicate likely configurations for standard hexapod motion platforms.

The paper proceeds as follows. Firstly, the motion literature concerning applications to rotorcraft is revisited for completeness, and the OMCT procedure is briefly introduced. Next, the experimental set-up for the investigation is presented including details regarding the simulation facility, motion algorithm and conditions, the task, the evaluation process and the pilots. Next, the results obtained are shown. Following the presentation of all results, a discussion is made and conclusions from the work are presented.

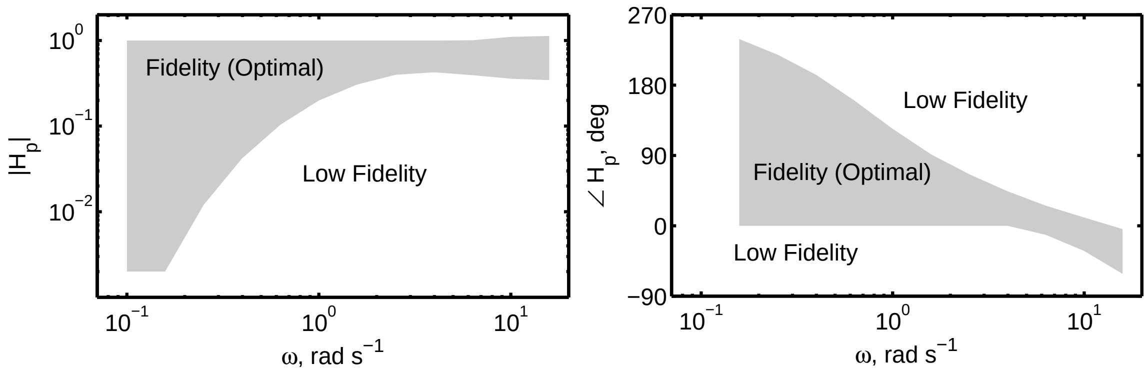


Figure 1: Example of OMCT boundaries: Test 3, roll response to roll input.

II. Rotorcraft Motion Literature

Much of the literature from a research standpoint was obtained from test campaigns undertaken using NASA's Vertical Motion Simulator (VMS), in particular the contributions of Sinacori[5] and Schroeder.[4] The latter work contains a detailed review of the state of the art at the time, which (at that time) was predominantly focussed on application of motion tuning for fixed-wing aircraft. From Schroeder's work, some of the first motion boundaries, obtained from objective and subjective evaluations, were proposed. The author considers these to be the most complete guidelines currently available for tuning efforts. During the investigations, the motion assessment was conducted during roll-sway, yaw, and heave cueing investigations.

Although the boundaries proposed in Ref. 4 are still used today, their relevance to modern motion systems is fading. This is in part due to the complexity of current motion algorithms. Schroeder's work was conducted using pure attenuation of motion gain. No 'washout' algorithm was employed. Due to the size of modern hexapod motion platforms, this method is not commonly used, particularly for training activities. Instead, to support the range of flying tasks undertaken in simulation, hexapod motion platforms require the use of washout algorithms. Although much research has been devoted to designing and testing complex adaptive algorithms, most current training simulators employ filters derived from the classical washout algorithm[13–15](CWA).

From investigations presented in Ref. 4, the roll-sway task has seen the most subsequent interest. The investigations were first extended by Mikula et al.[16] through the inclusion of a second-order washout algorithm. Using a very similar task set-up and approach, rotorcraft and fixed-wing motion usage was compared. Generally, boundaries found by Schroeder were validated through these investigations. These investigations however were also conducted in the VMS. Tran et al.[17] extended this research through a similar experiment conducted in the longitudinal axis.

More recently, Hodge et al.[6] completed further tests using a combination of techniques employed in the works cited above. For these investigations, a 'short-stroke' motion platform was used. Novel methods and approaches were introduced to assess motion fidelity for rotorcraft applications. Results in Ref. 6 were in disagreement with results from investigations detailed above. 'Good motion cues' were achieved with a much lower motion gain (ratio between vehicle and simulator motion amplitude) than originally stated. This was supported by objective and subjective data. In the investigation, the roll-sway task aggression was significantly increased from Schroeder and Mikula et al. campaigns. This is likely to have increased the false cueing during the investigation.

Finally, Wiskemann et al.[12] completed investigations using a robot-arm motion simulator. The available motion range of this simulator allowed Schroeder's investigations to be repeated. During these experiments, the conditions of the original investigations were reproduced. Motion attenuation was found to be more effective than applying large washout. The effects of washout in the low-pass (LP) channels were not investigated. It is also worth to mention that all pilots in the investigations had very low simulator hours, and were not test pilots. The validity of the subjective results is therefore questionable, as it is also acknowledged that the pilots had no experience awarding handling qualities ratings (HQRs).

A. Objective Motion Cueing Test

To solve the drawbacks of previous criteria and to implement a generic method for application on currently operational simulation devices, Hosman and Advani proposed a new test procedure, the OMCT. The OMCT technique is designed to both improve transparency of tuned motion systems and provide guidance for tuning efforts. The OMCT defines a series of sinusoidal inputs to the motion platform, designed to simulate possible vehicle motion. Input signals vary in magnitude and frequency. By measuring the output of the system, it is possible to determine the input/output relationship, i.e. motion gain and phase for each degree of freedom. Bode plots are then used to display results. As shown in Fig. 1, boundaries define the allowable motion gain and phase. The method extends the Schroeder metrics as follows:

- Includes both hardware and software in the results
- Tests the envelope of the motion platform from 0.1 Hz to 15 Hz
- Includes off-axis, LP channels, and cross coupling considerations

The method has gathered support from both research organisations and certification authorities (i.e. FAA). Furthermore, its application has sparked renewed interest in motion tuning research.[9,10,18,19] These range from its application, validation, and proposed extensions to the criteria. An outstanding issue with the use of OMCT are the boundaries used to determine fidelity. Rather than base the conception of the criteria on academic experimentation, Hosman and Advani focused on the applicability of the criteria to current flight simulation devices. Using 10 fixed-wing devices, with varying fidelity and uses, the OMCT was conducted. From these results, initial fidelity boundaries were proposed, based on the principle that these simulators had previously been designated as 'fit-for-purpose'.

Jones et al.[18] conducted an investigation to determine the sensitivity to changes in motion parameters for a number of typical rotorcraft flying tasks. Two simulation platforms were used, with one test pilot used in both facilities. In this research, Schroeder and OMCT boundaries were investigated. The results highlighted large differences between OMCT fixed-wing boundaries and requirements for completion of rotorcraft mission tasks. Degradation in performance was visible from objective data analysis. As in investigations by Wiskemann et al., the use of gain attenuation was found to be more suitable than an increase in washout. Similarly to the work presented by Hodge et al.,[6] novel assessment methods were presented. One problem found during the investigation was the difficulty to display OMCT results using the Bode plot representation. Feasible fidelity regions could not be proposed based upon the single boundary.

Parallel to the work described above, Dalmeijer et al.[19] investigated potential improvements to the OMCT through further analysis of the suitability of input signals. It was proposed that tailored inputs, specific to the vehicle and task, were used for the completion of the OMCT and not generic signals as currently proposed. Only limited piloted investigations were conducted and strong conclusions could not be drawn.

OMCT boundaries are also not in agreement with previous research regarding rotorcraft. In Ref. 20 it is shown that high-fidelity motion cueing can be obtained using much lower motion gain than allowable with current fixed-wing OMCT boundaries. One major benefit of OMCT is its ability to be applied within industry. It has been intentionally designed to be widely applicable, with the results understandable for not just motion experts, but also engineers with general knowledge of systems.

From the discussions in this section, there exists a lack of readily available, fully evaluated criteria for rotorcraft simulator platform tuning. Criteria proposed by Schroeder are established and robust. Their ease of application and intuitiveness has led to their continued application. However, the method does not robustly analyse the response of the complete motion system. OMCT criteria provide an assessment of the complete system however, current boundaries do not seem acceptable for rotorcraft simulation. Furthermore, the use of only Bode plots and a single per-axis boundary is yet to be proven sufficient. The current status of the criteria is motivation for this investigation.

III. Experimental Set-up

The simulation campaign was conducted to determine whether current criteria are applicable for rotorcraft manoeuvres. Furthermore, it was desirable to determine whether changes to the training efficacy occurred following changes to the motion configurations. This was conducted in the Air Vehicle Simulator (AVES) at the German Aerospace Center (DLR).

A. AVES Simulation Facility

The AVES simulation facility (see Fig. 2) was used for all investigations discussed in this research. AVES is maintained and developed by DLR. Its design centres around the ability to easily interchange aircraft cockpits for use on a single motion platform. Currently the facility features one fixed-wing cockpit (A320) and one helicopter cockpit (EC135). The motion platform features a hexapod structure, with six actuator legs to provide six degrees of freedom motion. The motion platform features a maximum actuator stroke of 1.5 m, meaning that the hardware is capable of reaching the highest requirements for training simulators.[21]

(a) External view. (b) EC135 cockpit.

Figure 2: Air Vehicle Simulator (AVES) at DLR.

The AVES EC135 cockpit is a replica of the aircraft type. The cockpit contains four seats: two pilots, a flight test engineer, and a simulator operator. The operator sits at the back of the cabin. Within the cockpit, hardware and software used in-flight, in the experimental helicopter ACT/FHS (Active Control Technology/Flying Helicopter Simulator), is also utilised. All flight experimental software to be tested in-flight is first tested in AVES. AVES is used both to support flight testing and to supplement or replace it when experimentation cannot be conducted in-flight. The two main reasons to replace flight tests with simulation testing are safety and reconfigurability. For example, due to the allowable operational envelope, it is not possible to fly the ACT/FHS offshore or during adverse weather conditions.

B. Motion Cueing Algorithm

The overwhelming majority of simulation devices currently used for training efforts feature a hexapod motion platform and a derivative of the CWA. This type of algorithm is also used in AVES. Figure 3 shows a simplified representation of the motion cueing algorithm used in AVES. This structure is used throughout these investigations. Using the CWA, translational and rotational motion of the platform is achieved through the use of a combination of high-pass (HP) and low-pass (LP) filtering elements. HP elements attenuate low-frequency motion, which left unfiltered would result in the requirement for very large motion travel. LP filtering elements provide cues in an attempt to replicate the low-frequency motion sensation lost through this HP filtering. LP cueing achieves this through additional rotational attitudes in both pitch and roll. This tilts the platform such that the gravity vector gives the human occupants the impression that they are experiencing a sustained acceleration.

Input to the motion algorithm is always vehicle specific force (i.e. force without gravity, $f_{x_{AA}}, f_{y_{AA}}, f_{z_{AA}}$) and, in the case of AVES, vehicle rotational acceleration ($\dot{p}_{AA}, \dot{q}_{AA}, \dot{r}_{AA}$). Rotational rate may also be used where appropriate. AVES uses standard third-order HP filtering for rotational channels (pitch, roll, yaw), and second-order LP filtering for tilt-coordination channels. The AVES translational motion filters feature adaptive elements to prevent the platform from reaching motion limits. This is provided by an advanced platform kinematics filter, which is proprietary software from the manufacturer. As a result, the dynamics of the translational filters cannot be easily modelled using standard third-order filters. It has however been confirmed through extensive testing that this adaptive filtering does not occur during normal operation of the platform, and only occurs when close to motion system limits.

In order to remain within motion travel limits, it is usually necessary to attenuate the maximum motion 'gain' of each motion axis. This can be performed either following initial input to the motion platform or

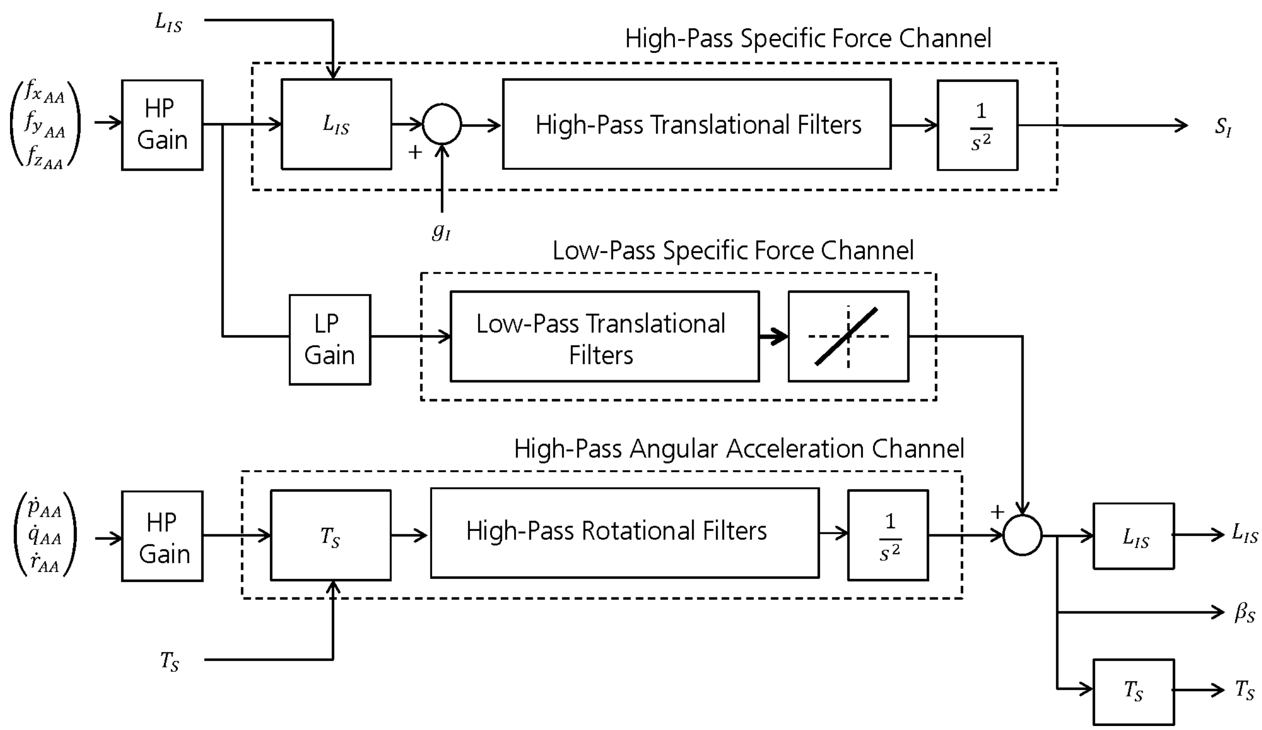


Figure 3: Classical washout algorithm structure.

within the HP and LP filtering elements. The usual scheme is to perform this as shown in Fig. 3. In previous work presented by the author, motion gain was dealt with within the filtering elements.

C. Motion Conditions and OMCT Results

One goal of this research was to determine the suitability of current OMCT boundaries. For this purpose, four motion configurations were selected. These were based upon typical tuned motion responses of the rotorcraft simulator, which may be used for training purposes. All motion cases were found to be suitable for the completion of the desired mission task element (MTE, discussed in the next section). This was confirmed through both pre-tests with pilot-in-the-loop flying and using desktop software of the motion platform.

The cases varied in motion amplitude and parameters of washout filters. The motion cases are referred to herein as LOW, BAL, WASH, and MAX. The motion filtering algorithm discussed in the preceding section was used to retain relevance to modern training simulators. Table 1 displays parameters used for the motion filters. Third-order filters in the rotational and heave channels are formed of a second-order HP filter and a first-order HP filter. The motion settings of the sway and surge HP channels include parameters for the adaptive elements and therefore are not included in the table below. OMCT results, characterising the response of the motion in these channels, are however shown in Fig. 4 and Fig. 5.

As rotorcraft MTEs usually feature multi-axis requirements, and the dynamics of the vehicle usually lead to cross-couplings between axes, motion cases were selected to offer similar levels of cueing in each axis. This ensures that the pilot does not perceive a mismatch in cueing due to large differences between axes. OMCT was completed for all of the motion configurations. Results are shown in Fig. 4 and Fig. 5 for on- and off-axis tests respectively. This was performed through mechanical testing of the motion platform. Boundaries from fixed-wing investigations were taken as guidance. However, due to the major differences between rotorcraft and fixed-wing flight, it is not entirely expected that boundaries will be suitable for rotorcraft flight tasks. The OMCT results were compared with two sets of fixed-wing boundaries: those presented by Hosman and Advani[2] and those more recently presented by Zaal, Schroeder, and Chung.[22] The former boundaries were developed through OMCT testing in 10 simulation facilities. The latter were developed through research test campaigns conducted in the VMS.

Table 1: Motion configurations

	Configuration				
Case	NO	LOW	BAL	WASH	MAX
High-pass filter gain (-)	0.0	0.2	0.4	0.4	0.7
Low-pass filter gain (-)	0.0	1.0	1.0	1.0	1.0
Pitch and roll second-order filter break frequency (rad/s)	-	0.3	0.3	0.8	0.8
Yaw second-order filter break frequency (rad/s)	-	0.5	1.0	1.0	1.0
Heave second-order filter break frequency (rad/s)	-	0.8	0.8	2.0	2.0
Low-pass second-order filter break frequency (rad/s)	-	4.0	4.0	4.0	4.0
High-pass second-order filter damping ratio (-)	-	0.9	0.9	0.9	0.9
Low-pass second-order filter damping ratio (-)	-	0.9	0.9	0.9	0.9
Pitch, roll, yaw, heave, first-order filter break frequency (rad/s)	-	0.1	0.1	0.1	0.1

The LOW motion case features the lowest motion gain (0.2 of the actual motion for all axis). With the low gain, the phase distortion of the motion setting is minimised for all axes. This motion case least reflects both sets of fixed-wing OMCT boundaries. The BAL case is considered to be ‘balanced motion’, as the filters are the result of a compromise between motion gain and motion washout. This case better reflects the OMCT boundaries, although does not meet requirements for pitch and surge response. The washout for this case is similar to the LOW case. The WASH case features higher motion washout, resulting from the higher cutoff frequency of the third-order motion filters. This allows for more aggressive manoeuvring in the flight envelope. Although washout for the case is higher, OMCT boundaries are generally still reached for the configuration. Finally, MAX is a large motion case, that is not achievable for the complete flight envelope of the helicopter. The motion gain for all axes was set at 0.7 of actual motion. To allow for this level of motion, washout must be increased in all axes (except heave where washout is large for all configurations). This is shown in the OMCT results. Despite the large washout, all cases are found to be within OMCT fixed-wing boundaries. A reservation of this case are the large phase distortions in surge and sway.

Comparison with proposed OMCT boundaries shows large differences between the two sets of boundaries. For the Advani-Hosman boundaries, the MAX motion case achieves 80% of the desired motion. For the same case however, using boundaries from Ref. 22, a success rate of only 10% is achieved.

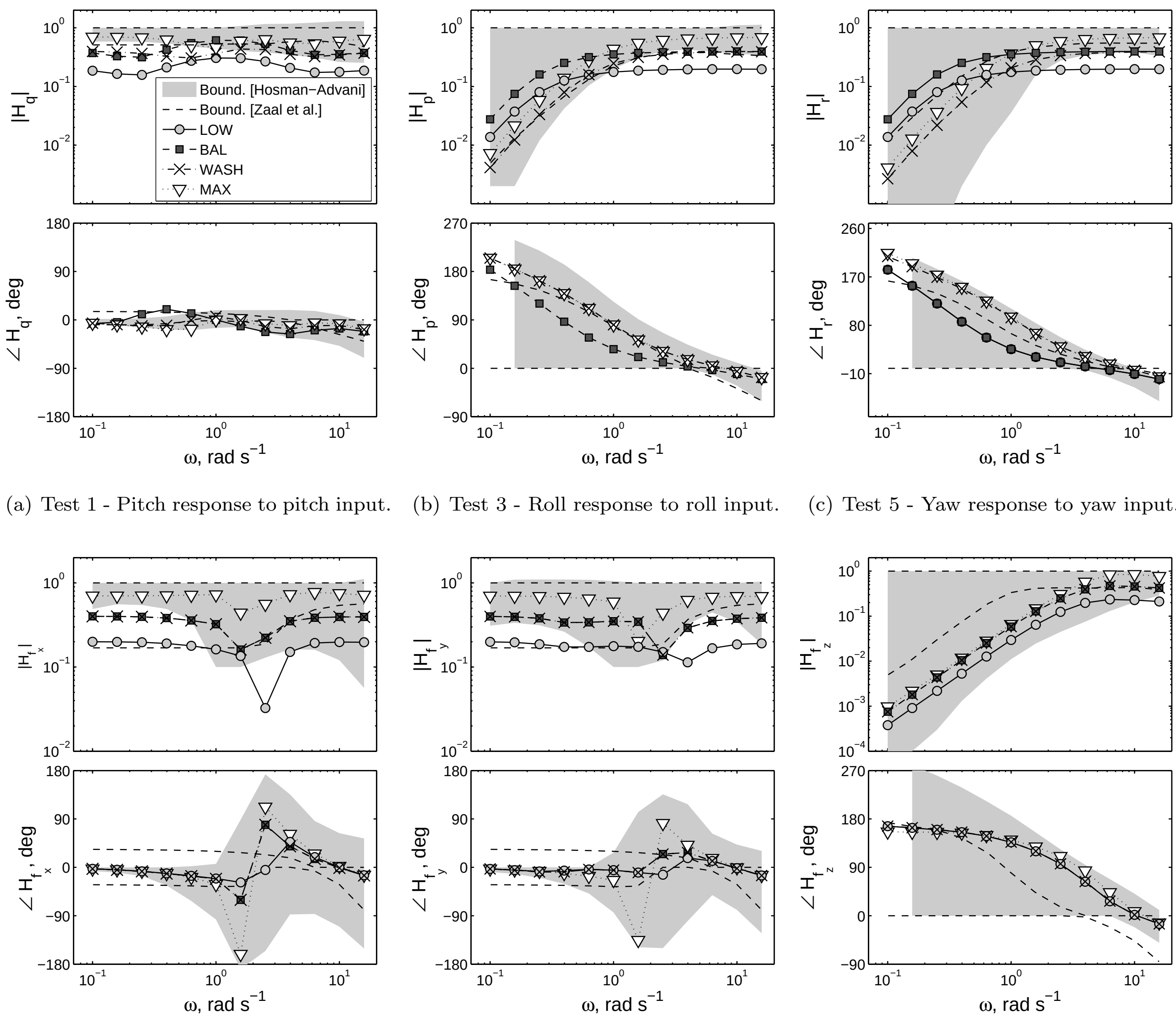
The motion cases are representative of what would be expected for simulation platforms: as the motion gain increases, so must the motion washout to prevent reaching limits. The case therefore with the largest washout is for the highest amplitude of motion. In terms of motion gain alone, the MAX case is most representative of ‘real-flight’. However, the LOW case has the lowest washout, which should minimise the false cueing resulting from phase distortions.

D. Tasks

In this study, the motion cases described above were flown for one MTE, the pirouette manoeuvre as detailed in ADS-33E-PRF.[23] This task represents a ‘typical’ mission requirement for rotorcraft, and therefore a typical scenario for which an FSTD should be used.

The pirouette is used to check the ability to accomplish precision control of the rotorcraft simultaneously in pitch, roll, yaw and heave axis. From an altitude of 10 ft, the pilot must accomplish a lateral translation around a circle, keeping the nose of the aircraft pointed at the centre of the circle, radius 100 ft. To achieve desired performance, completion of a full circle in 45 seconds, the pilot must maintain a constant groundspeed (GS) of approximately 8 kts. External references are preferred to allow the pilot to judge his/her performance. The external references, and tolerances used to complete the task, are shown in Fig. 6.

In comparison to previous work conducted to determine rotorcraft motion fidelity requirements, the pirouette task used here is more aggressive. The GS of approximately 8 kts must be maintained to achieve desired performance. In the roll-sway investigations described in Ref. 4, a GS of only 1-2 kts was required to complete the lateral translation. The increase in GS requires the pilot to initiate larger rotational motion. This has an influence on the false cueing, as discussed in the following section. To increase realism when



(a) Test 1 - Pitch response to pitch input. (b) Test 3 - Roll response to roll input. (c) Test 5 - Yaw response to yaw input.

(d) Test 6 - Surge response to surge input. (e) Test 8 - Sway response to sway input. (f) Test 10 - Heave response to heave input.

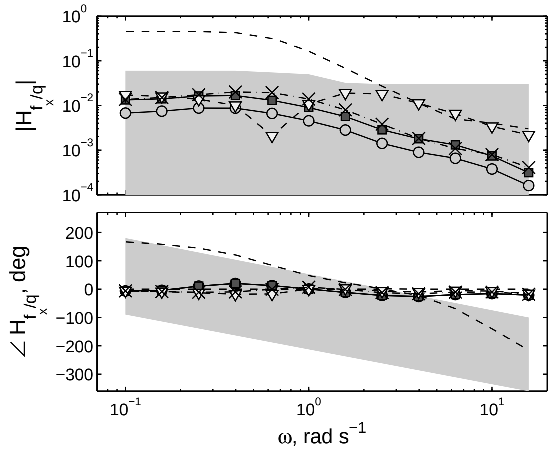
Figure 4: OMCT results for four motion configurations compared to two sets of boundaries - on-axis.

completing tasks, very calm turbulence was used. This is representative of the turbulence expected on a calm day. This differs from the manoeuvre description contained in ADS-33, whereby only 'calm wind' is required. The manoeuvre was flown only in the anti-clockwise direction due to time constraints. Prior to tests, the level of turbulence was confirmed as 'low' through the use of a DEF-STD rating.

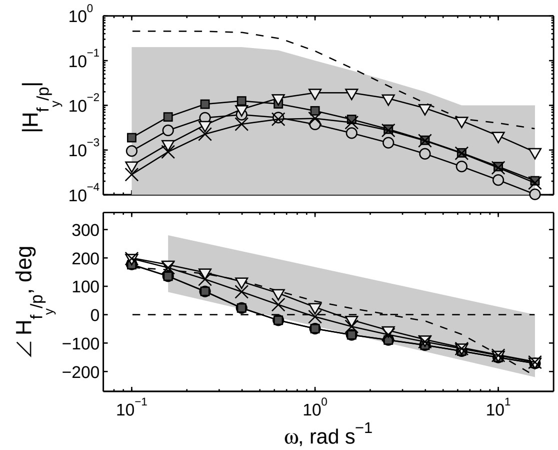
E. Test Procedure

In recent motion investigations, randomised test matrices have been employed, whereby the pilots fly each test run with a different motion case.[12,22] Previous experience with motion tests in AVES has shown that pilots find it challenging to assess motion fidelity following frequent changes to the configuration. It had often been noted in previous tests at DLR that pilots consistently compare the motion with 'the previous case'. Therefore, for this test campaign, a test process was developed to allow the pilot to assess the motion against the previous case. The procedure shown in Fig. 7 was developed.

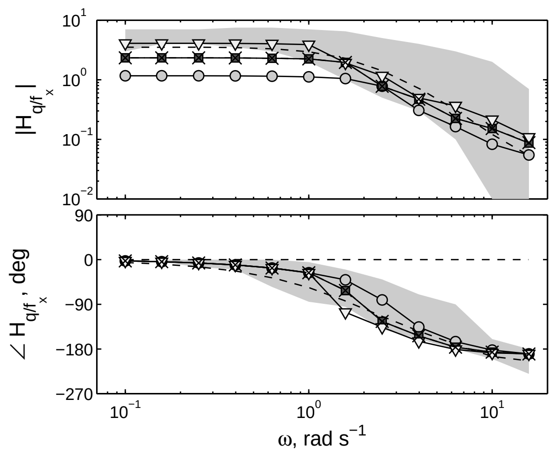
Firstly, pilots were requested to complete three 'training' runs, using a specific motion case. Following the completion of three training runs, the pilots were asked to award a Bedford Workload (BWR) and a Motion



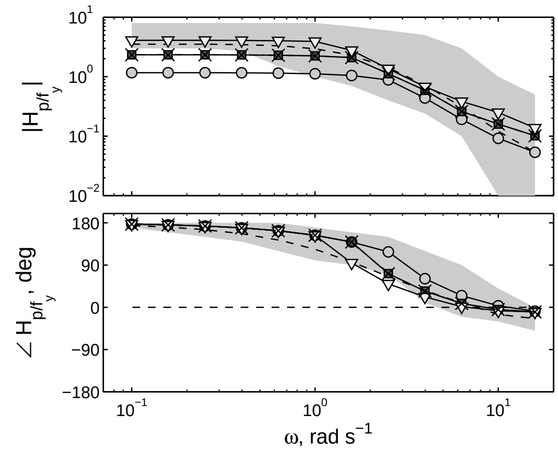
(a) Test 2 - Surge response to pitch input.



(b) Test 4 - Sway response to roll input.

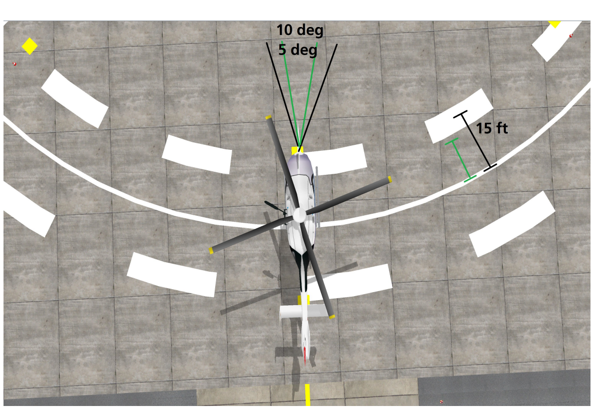


(c) Test 7 - Pitch response to surge input.

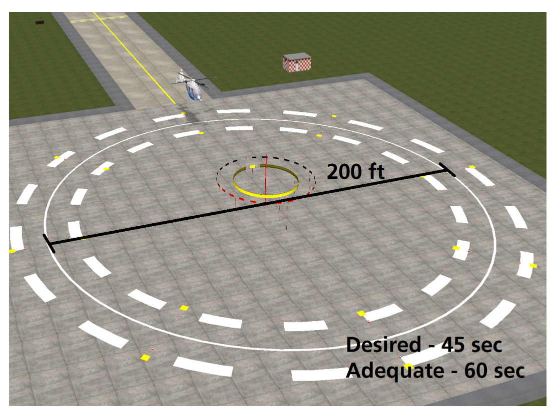


(d) Test 9 - Roll response to sway input.

Figure 5: OMCT results for four motion configurations compared to two sets of boundaries - off-axis.



(a) Top view.



(b) Course view.

Figure 6: Pirouette mission task element (MTE) performed in AVES.

Rating (MR). Assessment using BWR was preferred to Handling Qualities (HQ) ratings as the specific interest was to determine changes in pilot workload and not task performance. In previous investigations, pilots had commented that motion had influenced their workload but not their ability to complete the task

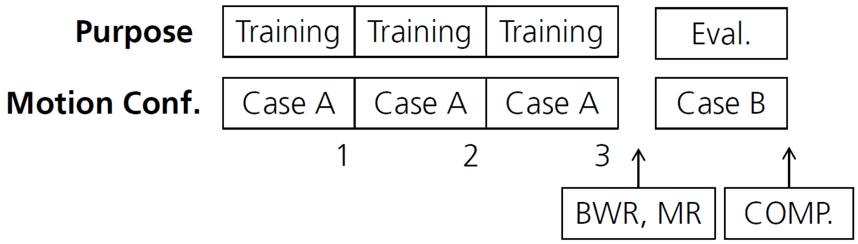


Figure 7: Test procedure used for the investigation.

performance requirements. For this reason, the Cooper-Harper HQ rating scale was found to have a low resolution for changes in motion configuration.

Following the assessment of the training case, the motion configuration was changed to an ‘evaluation case’. At this point, the pilot was allowed to fly the task only a single time (as he has previously trained using the training motion). Subsequently, following the evaluation run, pilots were asked to complete a questionnaire, providing a comparison of motion cases. The questions in Fig. 8 were used.

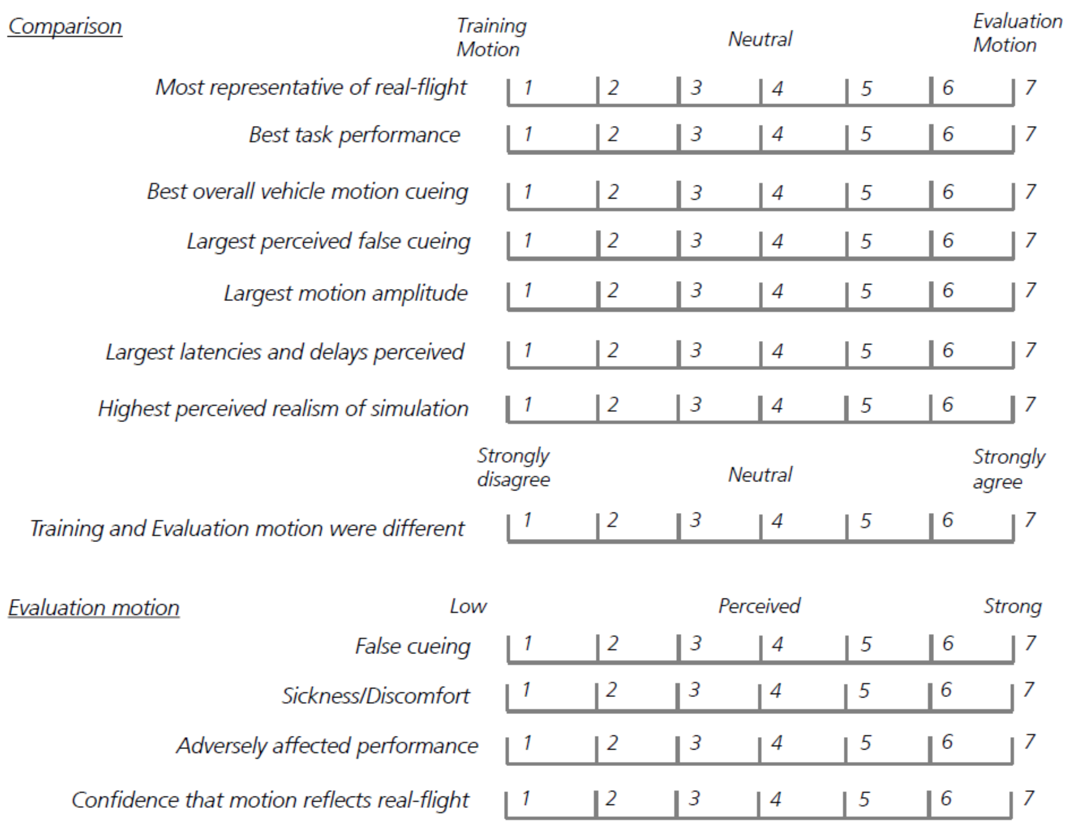


Figure 8: Pilot questionnaire used in study.

Questions 1-7 ask the pilot to directly compare the training motion with the evaluation motion. The eighth question asks the pilot to state whether he believed motion cases were different. Questions 9-12 ask the pilot to assess the evaluation motion (i.e. Case B) only.

Pilots were asked to award motion ratings using the scale shown in Fig. 9. This scale was developed and presented in Ref. 24 and compared to alternative motion assessment schemes in Ref 6. Terms have been modified in the scale used for this investigation, whereby ‘acceleration’ is used for each of the angular, translational, and vertical questions. This is based upon feedback obtained. Motion configurations were completed in a quasi-randomised pre-determined order, which was not the same for all pilots.

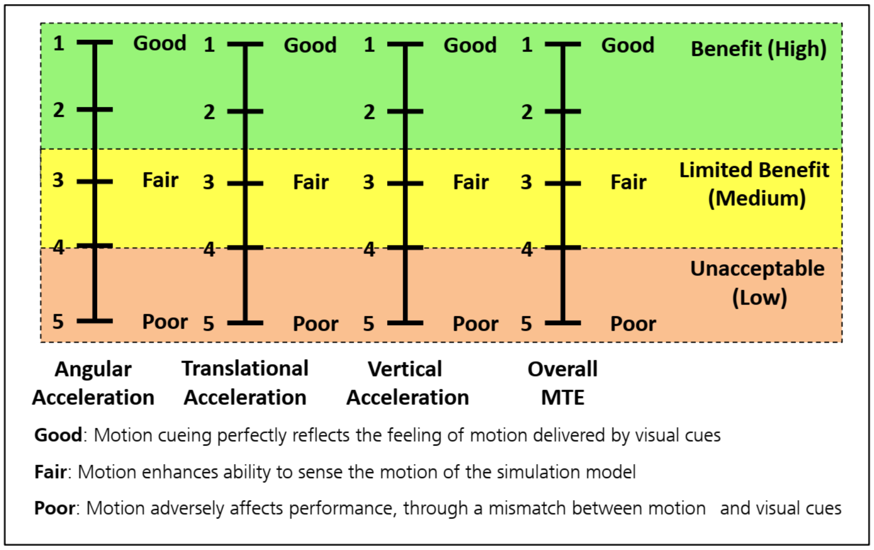


Figure 9: Motion rating scale.

Three motion configurations were used for training: NO, BAL, and MAX. Four motion configurations were used for evaluation runs: LOW, BAL, WASH, and MAX. An additional configuration (training motion LOW, evaluation motion BAL) was also completed. This generated a test matrix of 13 configurations. All pilots flew each combination of training-evaluation runs once. Therefore, each pilot completed a total of 39 training runs and 13 evaluation runs. Table 2 shows the training and evaluation pairs selected during the investigation.

Table 2: Test matrix of training-evaluation pairs

	Evaluation motion			
Training motion	LOW	BAL	WASH	MAX
NO	O	O	O	O
LOW	-	O	-	-
BAL	O	O	O	O
MAX	O	O	O	O

‘O’ - case flown by all pilots , ‘-’ - not flown

F. Pilots

Three pilots participated in the investigations. All were qualified experimental test pilots. Two of the pilots had significant experience flying the AVES simulator and the ACT/FHS helicopter (Pilots A and B). One pilot was flying in AVES for the first time and therefore was given significantly more practice before beginning tests (Pilot C). All pilots had previous experience using the BWR scale. Two of the pilots had previously used the MR scale.

IV. Results

A. Direct Motion Assessment

Figure 10 shows the ‘Overall MTE’ motion ratings obtained and Fig. 11 shows ratings for angular, translational, and vertical acceleration. Markers show the mean value obtained with respect to pilots, and the whiskers show the minimum and maximum ratings obtained. Motion ratings were collected following three training runs, prior to the evaluation run. For each training-evaluation pair, pilots awarded one MR. These are shown with respect to pilot. As shown, results are consistent but show an offset between pilots. Pilot A consistently rated the motion as higher benefit than Pilot B. However, all pilot ratings show that LOW motion was most beneficial, followed by BAL motion and MAX motion. Both Pilots B and C awarded ratings suggesting that the MAX motion was unacceptable, meaning that it adversely affected task performance. Fewer ratings were collected for the LOW case than for the other two cases.

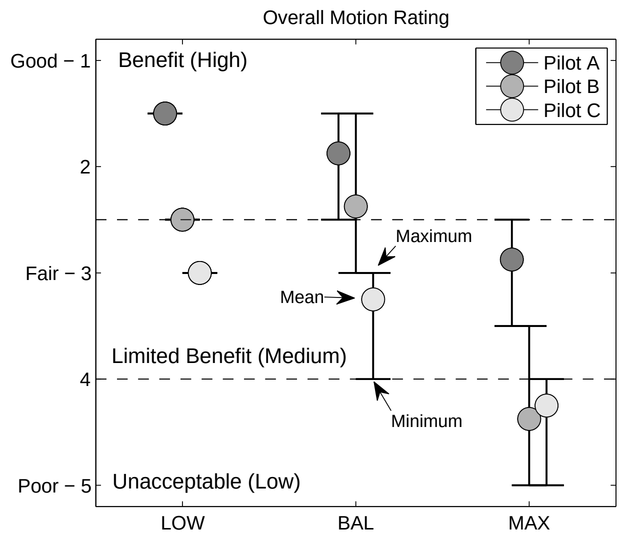


Figure 10: Overall subjective motion ratings.

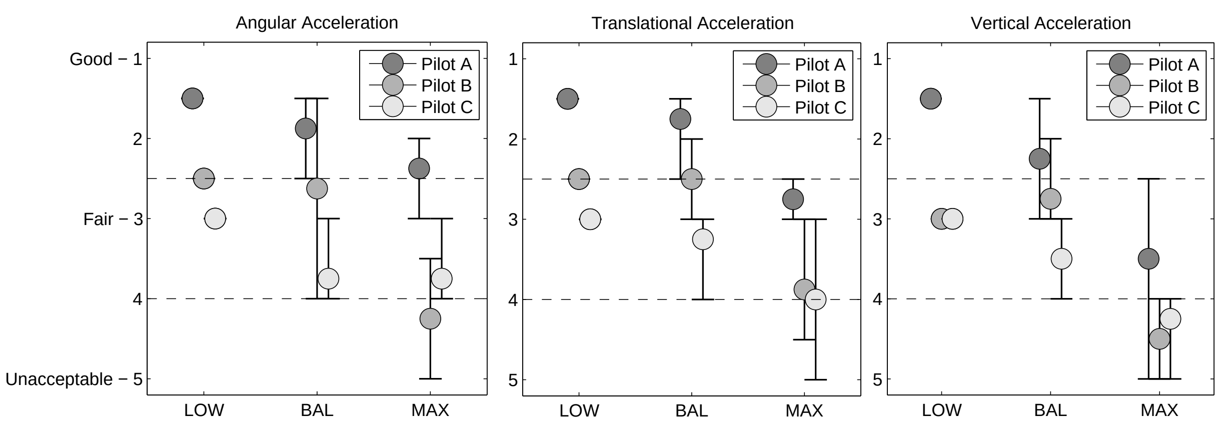


Figure 11: Subjective motion ratings for angular, translational, and vertical acceleration.

The initial results found from the awarded motion ratings were not directly expected - from the OMCT analysis shown in Fig. 4, if the current boundaries are to be used, the opposite is expected. The LOW motion is furthest from OMCT boundaries, primarily due to the low amplitude of the motion. The MAX motion is the only setting which meets all OMCT boundary requirements. However, this motion received the poorest subjective ratings. Immediately it seems there is a mismatch between OMCT boundaries and the fidelity.

Pilots also gave direct feedback of motion with questions 9-12. These results are shown with respect to pilot for the four motion configurations used for evaluation runs in Fig. 12. As shown, subjective opinion of false cueing was smallest within the LOW motion, and highest for the MAX motion. False cues due to false lean were calculated to be similar for both MAX and BAL motion. The differences in pilot subjective ratings suggest that further false cueing elements are apparent for the MAX motion case. It is likely that the pilots have detected motion washout, highest within the MAX case, as false cueing. This is likely the reason that BAL and WASH motion received similar false cueing ratings. For the BAL case false cueing can be attributed to the false lean cue. However, in the WASH motion case, false cueing is the result of large washout. The combination of both of these false cues is found for the MAX motion case. Further investigations are required to confirm this, but subjective results support this. Sickness was found to be highest for the MAX case. Pilot C, who had the least experience in AVES, was found to suffer the most from sickness. Pilot A was unaffected by changes to the motion parameters.

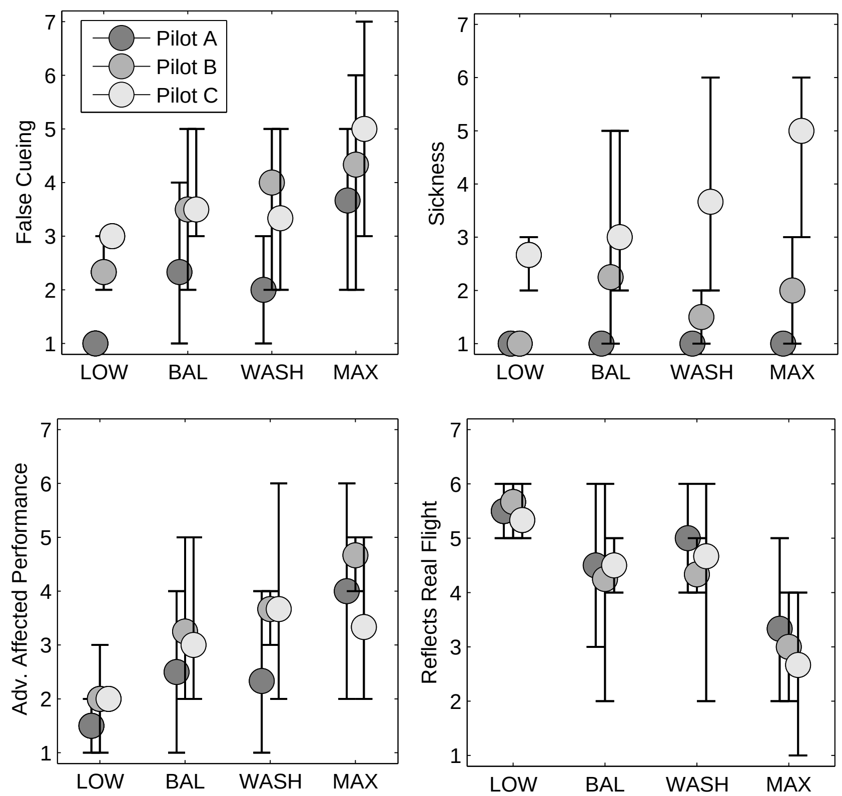


Figure 12: Subjective ratings obtained from questionnaire - direct motion appraisal.

The use of motion strongly changed the perception of turbulence to the pilot. During no motion cases, during some test points, the pilots were not aware that the turbulence was active. All pilots frequently commented that the turbulence level felt different with changes in motion settings. The MAX and WASH motion cases had the most significant adverse effect on performance. This is likely due to the motion washout.

All pilots were confident that the LOW motion case reflected real flight. This is despite the case having the lowest motion gain and least reflecting current OMCT fixed-wing boundaries. All pilots believed that the MAX motion least reflected real flight. This is again in contrast to the OMCT results, as this case most reflects current boundaries.

All ratings awarded by pilots were found to have a large spread. One reason for this was the variability of task performance for each motion case. Each motion assessment was dependent upon what the pilot had experienced during the completion of the test point. In some cases, pilots did not expose deficiencies, which in turn influenced the motion rating.

B. Impact on Workload and Task Performance

BWRs were taken to determine whether motion (or the lack of motion) caused any change in task workload. Figure 13 shows the ratings obtained, with respect to pilot. Fewer evaluations of the workload were conducted for the LOW case than for the other cases. Generally, an increase in workload was found for all pilots for the MAX motion case. Pilot A had the lowest sensitivity for changes in the motion configuration. Both Pilot B and C awarded ratings between 5-7 for the MAX motion case. This is in contrast to 3-6 for the NO motion case.

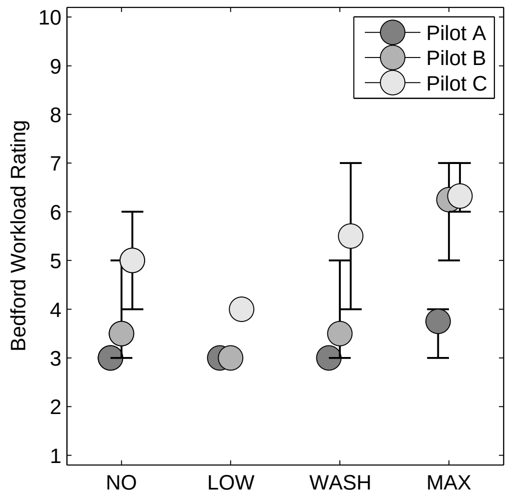


Figure 13: Bedford workload ratings.

Changes in the task performance are also apparent from objective measures. Figure 14 displays a number of objective parameters measured during completion of the pirouette manoeuvre. In the figure, the whiskers represent the maximum and minimum values, and the markers represent the mean values obtained. Results from all pilots are grouped. Objective parameters are for training runs only. Most relevant parameters were found to be: manoeuvre time, groundspeed (GS), maximum roll attitude (ϕ_{max}), maximum pitch attitude (θ_{max}), RMS roll attitude (RMS_ϕ) and RMS pitch attitude (RMS_θ).

One of the largest changes in objective performance was found to be manoeuvre completion time. Largest differences were found between the NO motion and other cases. For the NO motion case, pilots consistently reached desired performance standards, completing the manoeuvre with an average time of approximately 40 seconds. The LOW motion case was consistent with the NO motion performance. However, for BAL and MAX motion, desired performance was not always achievable. Average manoeuvre time increased. As shown in Fig. 14, maximum roll attitude and GS were found to decrease when motion was active (i.e. BAL and MAX motion).

Results show that pilots reduced their aggression when the motion was active. This is likely due to two factors. The first is the increase in realism when the motion is active (this is confirmed through further pilot assessment in the following section). Pilots reduce their aggression as they become more cautious of the situation (i.e. as in real flight). The second factor is likely due to the false cueing. All pilots commented that they experienced false cueing during both the BAL and MAX motion cases.

Figure 15 shows six examples of task performance with respect to ground position during completion of the pirouette manoeuvre. Performance is shown for cases with and without motion. All pirouette manoeuvres were completed anti-clockwise. Figures a) and b) display GS of first attempts to complete the manoeuvre with NO motion and MAX motion respectively. The MAX motion case was completed after the NO motion attempt. There are three main differences between the recorded trajectories during task completion. Firstly, the GS is higher in the NO motion case. GS remains high until reaching the end point. This leads to an overshoot during the stabilisation, a second difference to the MAX case. Thirdly, the ground position for the MAX motion case is much more variable than for the NO motion case. Oscillations in ground track are

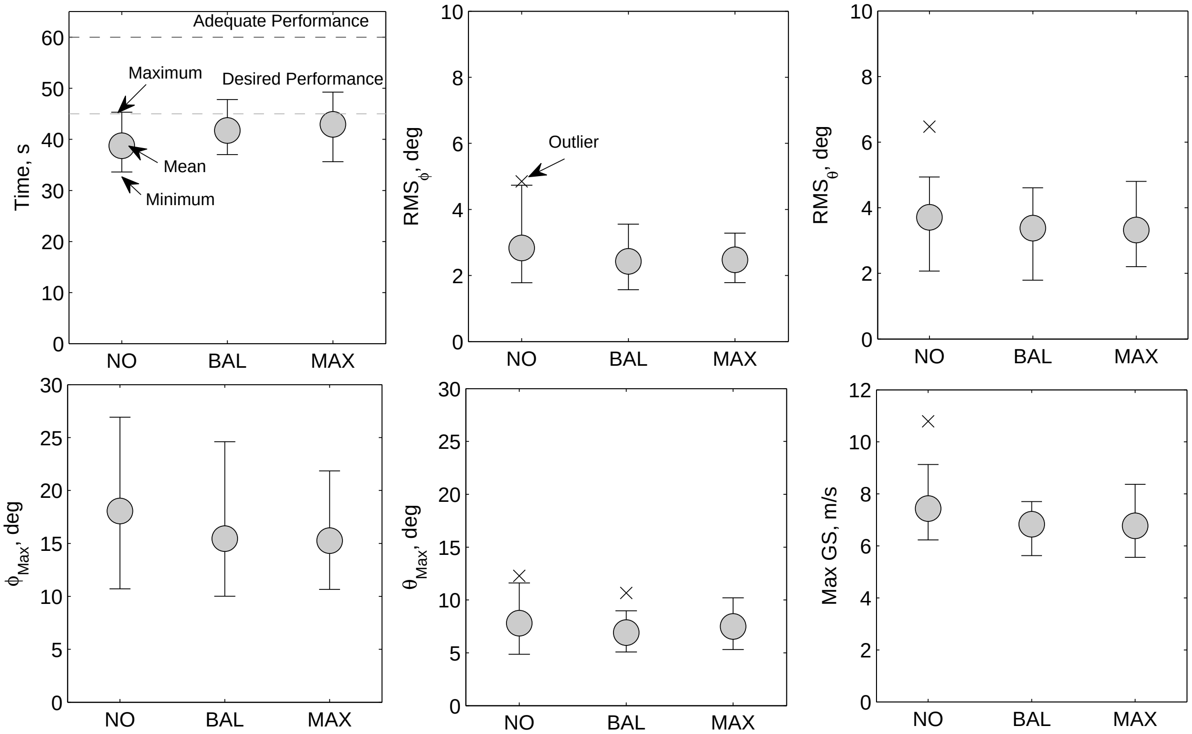
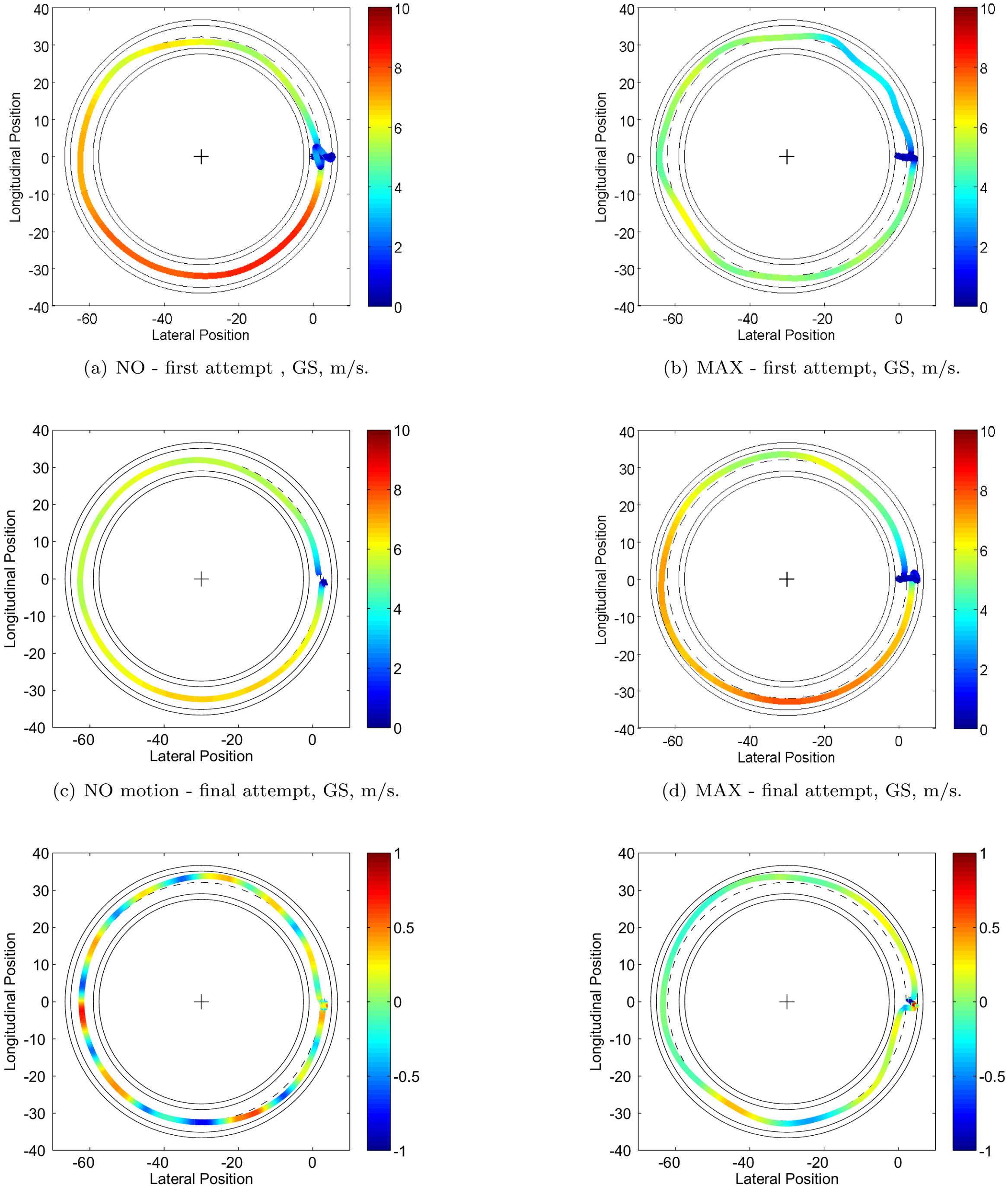


Figure 14: Most relevant objective parameters found during investigation.

apparent. Figures c) and d) show the last attempts of the NO and MAX motion cases. As shown, these are very different to the initial attempts, showing that the pilot has adapted to the changes in cueing. GS has significantly reduced for the NO motion case and increased for the MAX motion case. Despite significant training using the MAX motion, ground position during the stabilisation element of the task did not improve. This is in contrast to the NO motion case, where almost perfect performance was achieved.

Figures e) and f) display two cases of the vertical velocity recorded during the task completions. Pilots consistently commented that heave cueing was poor with all motion cases. Particularly with the MAX motion case, pilots had strong objections. Results show the difference between the vertical velocity for both NO and BAL motion. Results show that motion has led to a reduction in variation of the velocity, and therefore has improved task performance in this axis.



(a) NO - first attempt , GS, m/s.

(b) MAX - first attempt, GS, m/s.

(c) NO motion - final attempt, GS, m/s.

(d) MAX - final attempt, GS, m/s.

(e) NO motion - vertical velocity, m/s.

(f) BAL motion - vertical velocity, m/s.

Figure 15: Examples of performance with respect to ground position.

C. Comparison of Motion Cases

Comparison ratings were collected to compare all training and evaluation motion cases. Results from all pilots were generally found to be in good agreement, and were also found to reflect well the changes in the motion parameters. For example, all pilots correctly identified changes in motion gain. Figure 16 and Figure 17 show the results obtained with respect to training and evaluation motion. Table 3 gives an overview of the results obtained. The results confirmed the motion ratings obtained for the training motion sets. The comparison of the results also gave an indication that the LOW motion was preferred by the pilots. Results from Q1 - Q4, and Q7 show whether the motion is suitable. Q5 and Q6 could give an indication of how well the pilot perceives the motion.

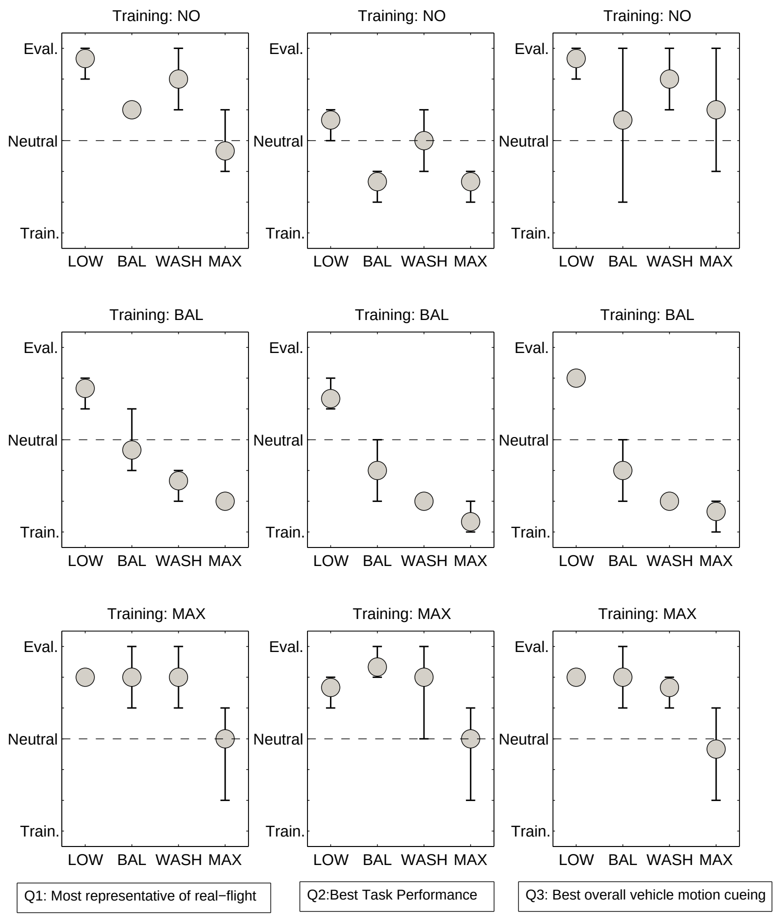


Figure 16: Subjective ratings - comparison between training and evaluation motion (i).

The results of the comparison suggest that the most suitable motion was the LOW case. This received best feedback for all Q1-Q4, Q7. The pilots unanimously agreed that the worst case was the MAX motion case. This case most reflects the OMCT boundaries. Concerning more recent boundaries from Ref. 22 however, this case does not reach requirements. Both surge and sway phase distortion, yaw gain and phase, heave gain and phase and pitch phase are outside of the more stringent boundaries. Of the three motion cases used for training cases (NO, BAL, and MAX), BAL was unanimously preferred to the MAX case. The perceived realism was higher, with lower delays, amplitude, and false cueing. A strong link was found between perceived false cueing (Q4) and latencies and delays (Q6). Furthermore, most representative (Q1) and highest perceived realism (Q7) were also closely linked. Generally, LOW, BAL, and WASH motion were considered more favourable than the NO motion condition. Pilots considered that the simulation was more realistic and more representative of real flight with these motion cases. It would then be considered that three of the motion cases (LOW, BAL and WASH) are suitable and one case (MAX) is not.

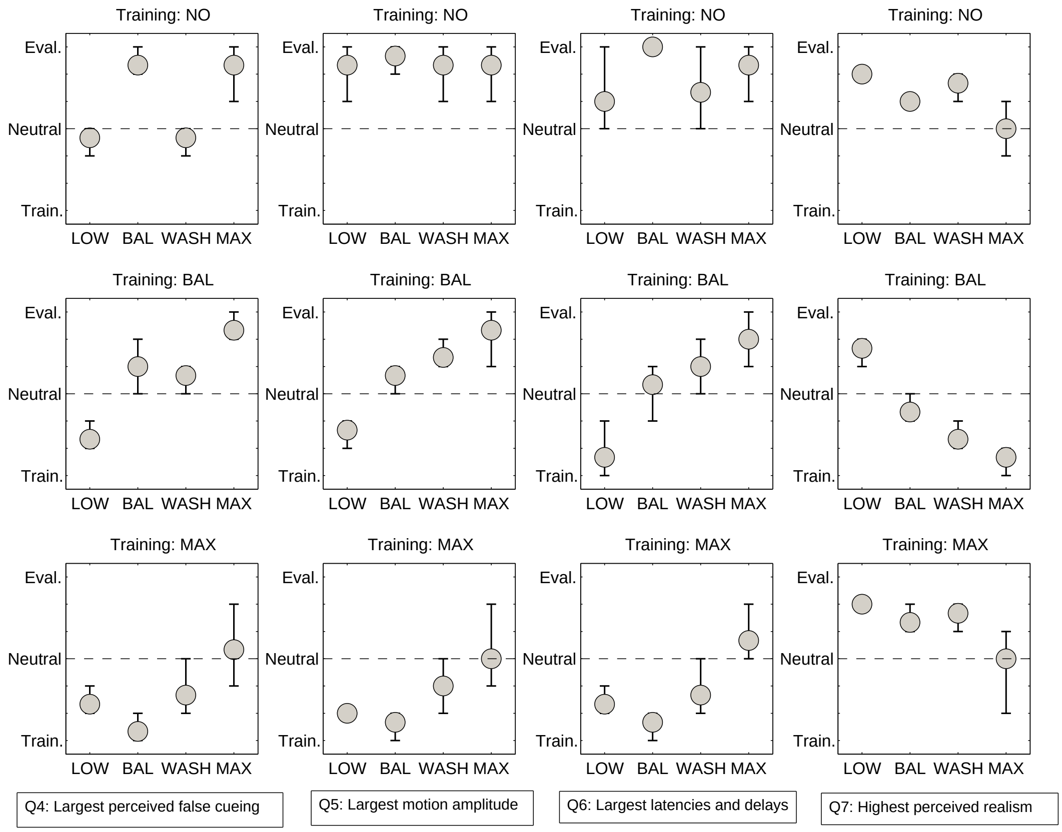


Figure 17: Subjective ratings - comparison between training and evaluation motion (ii).

V. Discussion

A. Correlation with OMCT Boundaries

The results from the investigation highlighted the differences between the pilots' subjective opinions and the current fixed-wing OMCT boundaries. This is in general agreement with previous investigations by the author.[18] Generally, through the pilot assessments and objective results, three motion configurations were found to be acceptable: LOW, BAL, and WASH. These motion configurations were found to have a higher perceived realism than the NO motion case. They were also considered to be more representative of flight than the NO motion case. Following OMCT, the BAL and WASH cases were generally found to be within the boundaries with the exception of pitch and surge response. The higher gain attenuation of the LOW case meant that this was not found to be in the OMCT boundaries. In this study, no evidence was found to suggest that the low motion gain was insufficient for realistic simulation. Generally pilots had a preference for this case. Through ratings and comments awarded, this appears to be strongly linked with perceived false cueing (see Fig. 12). Rather than ensuring that a specified motion gain is reached, it appears far more necessary to ensure that a) motion washout is not sensed by the pilot and b) false cueing is minimised. Both of these were consistently critiqued during pilot feedback.

Based on results obtained in this investigation, it is not possible to suggest suitable boundaries for tuning rotational axes, based only upon observation of the Bode plots. For both roll and yaw axes, referring back to Fig. 4, a boundary would be required to ensure that $G_i < 0.4$. This is counter-intuitive, as real-motion would feature $G_i = 1$, independent from frequency. For translational axes, a suitable boundary can be drawn with respect to phase requirements to encompass LOW, BAL, and WASH motion cases.

The benefit and subsequent 'fitness for purpose' of motion is extremely dependent upon the task and

Table 3: Summary of comparison results

No	Question	Best	Worst	Hypothesis
1	Most representative of real-flight	LOW	MAX	Large delays and false cues lead to poor representation of real flight
2	Task performance	LOW	MAX	Motion feedback has improved task performance with respect to NO motion, false cueing deteriorates task performance
3	Overall vehicle motion cueing	LOW	MAX	Delays and false cues deteriorate the overall cueing quality
4	Perceived false cueing	LOW	MAX	Lower motion gain masks/reduces false cues. Parasitic effects begin to become prominent with higher motion amplitude
5	Motion amplitude	MAX	NO	Motion gain is perceived by the pilot as larger motion amplitude, higher initial accelerations
6	Latencies and delays perceived	NO/LOW	MAX	Latencies and delays increase as motion gain increases, required for the motion to remain within the operational envelope
7	Highest perceived realism of simulation	LOW	MAX	Large delays and false cues not apparent with lower motion gain, no washout detected, improves realism

how the pilot performs it. This has been recognised during previous investigations. For this reason, it is very difficult to conclude on a standard set of boundaries for tuned motion. Rather, the focus should perhaps shift to a standardised test process.

This research effort has highlighted a strong difference between fixed-wing boundaries and rotorcraft requirements. There are three primary aspects where rotorcraft operations significantly differ from fixed-wing operations:

- Visibility (with respect to ground): Fixed-wing training exercises are usually conducted at altitude, due to the nature of operational tasks. Only the take-off and landing are elements of flight where strong feedback from the visual movement of the ground is experienced. A high proportion of rotorcraft training tasks are conducted at low level, where feedback from the visual environment is strong. Without motion from visuals (e.g. degraded visual environment), it is only possible for the pilot to relate the motion of the vehicle to the control input. The delay in this response is a factor of both the motion and the vehicle characteristics.

- Pilot control requirements: Fixed-wing operations are usually conducted using low-frequency, sporadic control inputs. Furthermore, much of the flying is conducted using an autopilot or flight director system. Pilots will not only command the vehicle using a control inceptor, but also using switches and dials. In this respect, it is very difficult to determine any delays in the system.

- Vehicle stability: Usually, fixed-wing vehicles are stable and pilots are not required to intervene unless manoeuvring is required. A further example of pilot intervention is during failures. However, during these manoeuvres, usually pilots do not have sufficient temporal capacity to assess the motion response. Moreover, the situation is usually irregular, and pilots may struggle to appreciate whether the response is realistic. Operational rotorcraft are usually unstable. This is due to the inherent stability modes of the vehicle. Constant pilot involvement and correction is required, at closed-loop frequencies above 2 rad/s.

During these investigations, for some test cases, a high scatter in pilot ratings and variability was found. This was due to differences in task performance. Changes in the vehicle dynamics led to different characteristics and motion.

B. Comparison of Motion

Objectively, the presence of larger motion cueing had the effect to reduce initial vehicle accelerations. This was clearly shown when starting the manoeuvre, with pilots more cautious to enter the manoeuvre. Without the motion, the manoeuvre completion time was found to be faster. Therefore, the presence of motion has influenced the task performance. Training in a simulator without motion would likely lead to higher vehicle accelerations than in real flight. This could expose deficiencies and HQs that would not be expected during normal operations.

C. Rotorcraft Training Simulator Requirements

No strong trends were found in the objective data to support (or discredit) a particular motion case. Only a limited number of evaluation runs were conducted, due to time considerations. Furthermore, without having access to 'truth data' from in-flight measurements of the task, it is challenging to draw too many conclusions from objective task performance. For example, with regards to the task completion time. If this were completed in the aircraft, it is not possible to know if the task time would reflect that with or without motion.

Subjective data clearly supported the use of specific motion cases. This was generally unanimous amongst the experienced pilots used in the investigation. Motion significantly affected the perceived fidelity of the simulation. An aspect that could not be tested in this investigation, but is likely to have detrimental effect on training, was the performance following sustained operation with each of the motion configurations. Two of the pilots (B and C) reported strong objections to the MAX motion case. One of these pilots (C) reported levels of sickness. Pilots were only exposed to the motion configuration for a couple of minutes. However, if the pilots were forced to train for long periods of time using the motion, it is hypothesised that the levels of sickness would increase, and the training significance would reduce. This may be caused by a reduction in concentration levels during the tests. Pilot A reported no sickness throughout, despite recognising false cueing just as the other pilots.

One difference was the level of turbulence sensed by the pilot during completion of test manoeuvres. Feedback from pilots throughout the campaigns was collected on the influence of turbulence. It was apparent that using different motion settings, the feeling of turbulence delivered to the pilot was contrasting. With no or little motion, on many occasions the pilots did not feel the turbulence and were very unsure as to whether motions of the vehicle were due to poor HQs or the influence of turbulence. As motion gain increased, turbulence became more noticeable as vibrations in the cockpit were visible. When using the motion case with the highest gain (MAX), pilots clearly felt feedback through turbulence within the cabin.

For training simulators, results here suggest that the main effect of vestibular cueing is a significant increase in perceptual fidelity. With this limited testing, it is not possible to say whether the absence of motion cueing will lead to a reduction in training efficacy for flight turbulence. This will be a topic proposed for future research in this area. As shown by pilot assessment, sometimes no motion is better than motion.

D. False Cueing

Due to the limited motion envelope of hexapod simulation platforms, it is almost always inevitable that a pilot experiences motion cues (i.e. accelerations and rates) that are different from the ones s/he experiences in real flight when flying the same manoeuvre. These differences are called "false cues". Subjective feedback during the investigation highlighted false cueing, particularly for cases with larger motion amplitude. There are a number of false cues that should be considered when tuning motion platforms. These are dependent upon the properties of the motion algorithm. A full and detailed description of sources of false cueing is contained in Ref. 8. It should also be noted that additional false cues exist, which may have also influenced the subjective and objective performance. These false cues are from the parasitic effects of the platform, which generally become more noticeable as the motion increases. One of the false cues that could not be completely prevented during the investigations was the sound. Despite efforts to mask the sound of the actuators, it was often not possible. Larger motion travel led to louder feedback. As the motion increases, parasitic effects become more noticeable. This also exposed nuances in the vehicle that were not clearly sensed without the large motion. Small vibrations were sometimes recognised when operating with the largest motion. These did not appear to influence task performance. Another potential problem was the return-to-neutral properties of the platform following completion of test points. On some occasions, for high levels of motion, motion was slow to washout and for some seconds a difference was experienced between motion and visual displays. The experimenter should sufficiently react to avoid this false cue, as it could significantly increase occupant sickness.

E. A Novel Metric to Supplement OMCT?

As discussed above, using current OMCT boundaries and displaying the results only using the Bode plot representation does not appear enough to draw a unified boundary, particularly for rotational motion. This was also found in previous investigations. One aspect not covered by the boundaries shown in Bode plots is the change in motion gain and phase. The change in motion as a metric for determining the quality of motion was recognised in previous work by the author.[24] Fitness functions were defined for the optimisation of motion cueing sets. Figure 18 shows the typical response of a third-order motion filter. The shaded region represents the typical range of motion frequency during closed-loop piloted control (0.5 rad/s and 10 rad/s). Pilot control is expected in the region of 0.5-2.0 rad/s, and the semicircular canals, used for angular motion rate detection, have been measured as accurate between 0.6-15 rad/s. In this range, the pilot is likely to detect changes in rotational motion. The parameter ΔG_i is the difference between the maximum and minimum motion gain in the range of observation. Calculation of ΔG_i is possible following the completion of the OMCT.

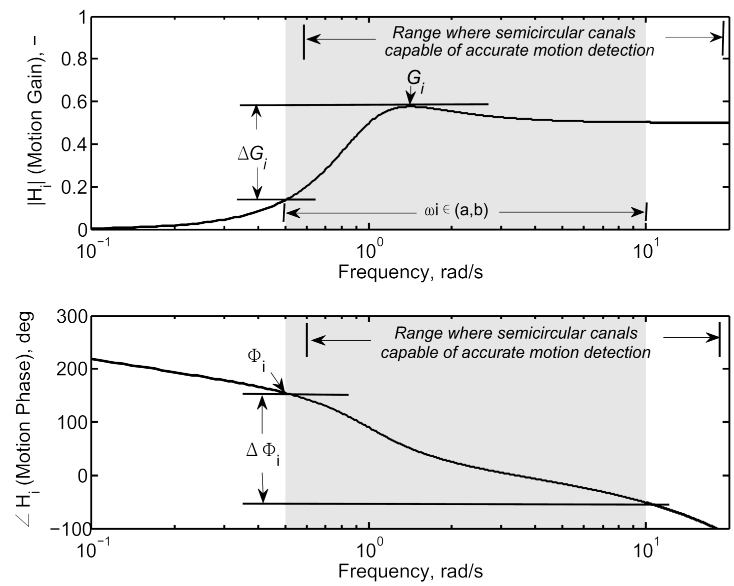


Figure 18: Response of typical washout filter with respect to frequency.

Figure 19 shows ΔG_i (change in G_i) for both the roll axis and the surge axis for the four motion configurations investigated. Investigations found pilot preference for LOW and BAL motion cases, whilst the WASH case was deemed acceptable. The MAX case was found to be unacceptable. For the rotational channels, based on results of the investigation, it is possible to draw a tentative boundary between suitable and unsuitable cases. This is displayed in Fig. 19 and is only an initial suggestion. Using results obtained from this investigation, it is not possible to draw a boundary to distinguish between suitable and unsuitable motion in the surge and sway axes. Further investigations could also be undertaken to find a suitable preliminary boundary. Figure 20 displays changes in G_p with respect to overall motion rating obtained during this investigation and a previous investigation by the author. As shown, a correlation between rating and the change in G_p is found.

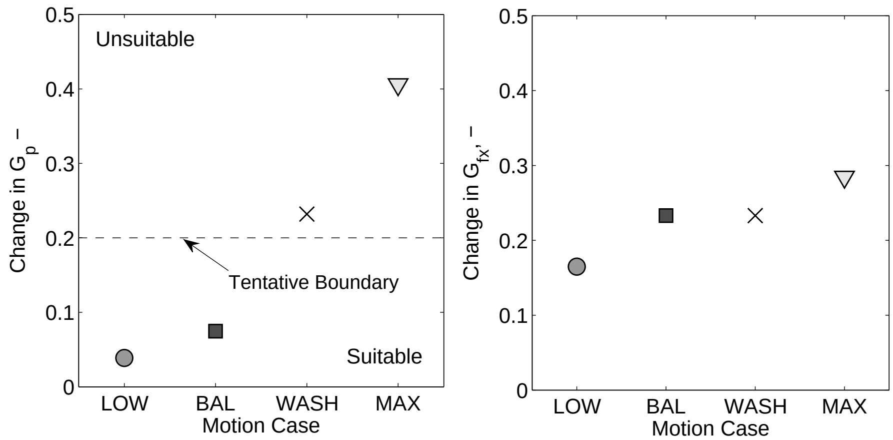


Figure 19: Change in gain for roll axis and surge force.

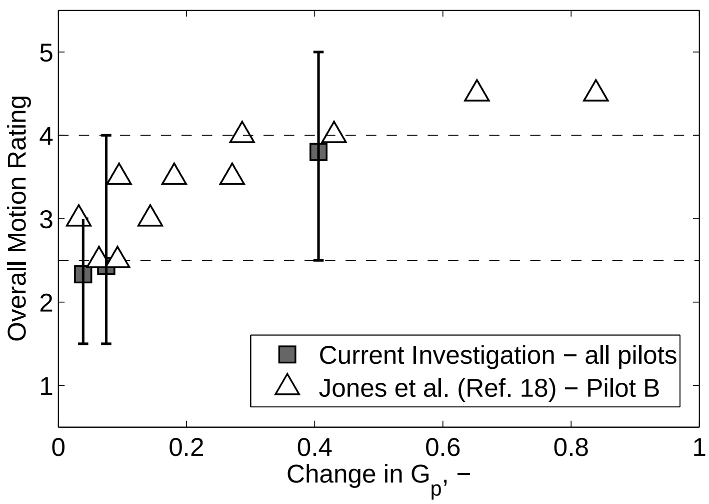


Figure 20: Comparison between change in roll gain and subjective motion rating.

VI. Conclusions

The following are the key conclusions from this investigation:

- Pilots clearly recognised differences between motion configurations. The strongest consequence appears to be a reduction in aggression during the task, resulting in longer manoeuvre completion time, lower attitudes and rates, and groundspeed. Slight reduction in task performance was also found using one of the motion cases. In a training sense, motion appears to teach pilots to apply an appropriate control strategy as if they were flying the vehicle.
- The test procedure of flying training and evaluation runs was considered to be successful. The pilots' ability to judge differences between motion configurations was generally confirmed through results. For example, pilots always correctly determined the relative motion gain.
- Although the turbulence was very low throughout the testing, the pilot perception of the turbulence was found to be strongly influenced by the motion configuration. Pilots consistently commented that they either could not sense turbulence without motion or the turbulence was significantly weaker. From a training aspect, it appears that the ability to recognise turbulence requires the use of motion cueing.

- OMCT boundaries alone, using only Bode plot representations, were not suitable to draw proposed boundaries for acceptable motion settings. An additional measure, the change in motion gain, is proposed. This measure was found to correlate well with motion ratings awarded by pilots during this and a previous investigation.

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